Attaining whole-ecosystem warming using air and deep-soil heating methods with an elevated CO$_2$ atmosphere

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**Objectives:**

- Measurements through time and across space have shown that the responses of terrestrial ecosystems to both chronic and acute perturbations of climatic and atmospheric drivers can lead to changes in ecosystem structure and function.
- The projected magnitudes and rates of future climatic and atmospheric changes exceed conditions exhibited during past and current interannual variations or extreme events and thus represent conditions whose ecosystem-scale responses may only be studied through manipulations at the field scale.
- This paper describes the operational methods applied to achieve both deep-soil heating, or in this case, deep peat heating and whole-ecosystem warming (WEW) in tall-stature, high-carbon, boreal forest peatlands.
- The methodology produced systems capable of producing warming at multiple temperature levels in larger plots (> 100 m$^2$) and throughout the soil profile (depths well below 1 m) and above tall vegetation, and was deployed into a black spruce – Sphagnum peat bog in northern Minnesota as a platform for the Spruce and Peatland Response Under Climatic and Environmental Change (SPRUCE) experiment.
- Elevated CO$_2$ was also incorporated to test how temperature responses may be modified by atmospheric CO$_2$ effects on carbon cycle processes.
- The in situ WEW method is compared and contrasted with closely related field-warming approaches using both aboveground (air or infrared heating) and below ground-warming methods.

**New Science:**

- Although there has been considerable discussion of the utility and merits of various warming methods in recent years the authors find that the air-warming and deep-soil warming methods used in the study are appropriate for warming a tall-stature ecosystem (3 to 7 m) with active root and microbial populations (> −2 m).
- The WEW approach was successful in sustaining a wide range of aboveground and belowground temperature treatments (+0, +2.25, +4.5, +6.75 and +9 °C) in large 115 m$^2$ open-topped enclosures with elevated CO$_2$ treatments (+0 to +500 ppm).
- The WEW enclosures are able to maintain the full range of warming treatments over external wind velocities ranging from 0 to as much as 6 m s$^{-1}$.
- The system allowed for the application of the warming treatments largely uninterrupted throughout a full annual cycle.
- Air warming across the entire 10-enclosure study required ~ 90 % of the total energy for WEW ranging from 64,283 mega Joules (MJ) d$^{-1}$ during the warm season to 80,102 MJ d$^{-1}$ during cold months.
• Soil warming across the study required only 1.3 to 1.9 % of the energy used ranging from 954 to 1782 MJ d\(^{-1}\) of energy in the warm and cold seasons, respectively.
• Sustained temperature and elevated CO\(_2\) treatments were only constrained by occasional high external winds.

**Significance:**
• A number of reviews have recently called for new studies of climate extremes, including experimental warming, to obtain measurements for warming scenarios that go beyond the observable records.
• The large SPRUCE WEW enclosures utilized in this experiment allow for ongoing ecosystem-level assessments of warming responses for vegetation growth and mortality, phenology changes, changing microbial community composition and function, biogeochemical cycles and associated net greenhouse gas emissions.
• The WEW system described is capable of providing a broad range of warming conditions up to +9 °C with minimal artifacts from the experimental infrastructure, with the end result of an experiment system capable of giving scientists a fair glimpse of organism and ecosystem responses for plausible future warming scenarios that cannot be measured today or extracted from the historical record.
• Deep-soil-warming protocols modified for SPRUCE are also being adopted in other recent ecosystem studies, such as whole-soil and mesocosm warming experiments conducted in mineral soil and a saltmarsh-warming study in Maryland, which is using a modification of the deep soil heating approach.
• The warming treatments provide a reasonable approximation of projected future climate and atmospheric boundary conditions within which to study a full range of vegetation, microbial and biogeochemical cycling responses.

**Availability of Associated Data Products:**
• Current and archived PHENOCAM images for the SPRUCE plots can be found at https://phenocam.sr.unh.edu/webcam/gallery/
• Details of the SPRUCE experiment as well as plot-by-plot temperature data for both belowground and aboveground heating are available for viewing at the web portals http://mnspruce.ornl.gov and http://sprucedata.ornl.gov
• SPRUCE Experiment data have been archived at cdiac: Hanson, P. J., Riggs, J. S., Nettles, W. R., Krassovski, M. B., and Hook, L. A. 2016. SPRUCE Whole Ecosystems Warming (WEW) Environmental Data Beginning August 2015, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, USA, doi:10.3334/CDIAC/spruce.032
Aerial photograph of the SPRUCE experimental site on 5 August 2015. Plot numbers (1 to 21) and assigned temperature treatments are superimposed on the image. Dashed circles indicated established plot centers for plots that are monitored annually for tree growth. Plots 4, 10, 11, 16 and 19 receive elevated CO\textsuperscript{2}. The middle boardwalk is 112 m long.

(a) Diagram of the air-warming enclosure, warm air flow pattern and external wind inputs leading to a homogenized air envelope that surrounds the aboveground vegetation. (b) Diagram of the belowground heater distribution pattern and the functional heating surfaces. The 100 W heaters are deployed in an inner section A (seven deep only heaters), middle section B (12 deep only heaters) and outer section C (three alternating circuits of 48 full length heaters).

Daily mean air temperatures (upper graph) and the associated air temperature differentials at +2 m above the bog surface (lower graph) by treatment plots since 2014, including periods prior to enclosure construction (through January 2015), a period when upper enclosures were in place (January to July 2015), and observations since full enclosure of each plot was achieved (27 July through 5 August 2015). Interior blower function was initiated at the time of full plot enclosure. The sustained period of warming began at 14:00 on 12 August 2015. Differential temperatures are referenced to sensors within the fully constructed but no-energy-added control plot 6. Unchambered ambient plot data are also shown as T – 2 plots.